BEAM LOSSES THROUGH THE LHC OPERATIONAL CYCLE IN 2012

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Abstract

We review the losses through the nominal LHC cycle for physics operation in 2012. The loss patterns are studied and categorized according to timescale, distribution, time in the cycle, which bunches are affected, whether coherent or incoherent. Possible causes and correlations are identified, e.g. to machine parameters or instability signatures. A comparison with losses in the previous years of operation is also shown.

INTRODUCTION

In cycling accelerators the beam intensity evolution in the cycle is studied. Losses showing reproducible features might help identify which machine parameters to modify to improve transmission. During operation before 2012, losses at the LHC were negligible before collisions and transmission from the start of the energy ramp to collisions was very close to 100%, apart from few fills with beam parameters away from optimum values.

For the 2012 run, "tight" collimator settings [1] were chosen for physics operation so to guarantee protection even with β^* as low as 60 cm at the physics experiments ATLAS and CMS. Collimator jaws closer to the beam resulted in higher losses compared to previous years as more beam tails were consistently scraped away. Additionally, the increased impedance from closed collimator jaws is considered one of the causes for the instabilities that were observed throughout proton physics operation [2]. These factors resulted in an overall transmission (from end of injection to start of collisions) that was appreciably lower than 100% and losses that were about a factor 10 higher than in the previous years. The LHC operational cycle for physics is divided in "beam modes", or phases. Of interest here are is the first part of acceleration, between 450 GeV and 500 GeV (i.e. capture losses); the second part of acceleration, between 500 GeV and 4 TeV (here called Ramp), Flat Top, betatron Squeeze, Adjust, Stable Beams (only the first 5 minutes in Stable Beams are analysed).

In this document we attempt a first thorough study of the losses in the LHC proton physics fills cycle. The study is targeted to 2012, with an eye to 2011 for comparison. The losses are first studied depending on the beam mode so that a possible correlation to major machine settings change can be highlighted. Then we look at reproducible structures in bunch-by-bunch differences.

BEAM LOSSES PER BEAM MODE

In the following analysis, the intensity difference between the start and the end of a given beam mode is analysed over the year and correlated with setting changes. The data was extracted for all proton physics fills of 2012 that reached 4 TeV (from fill 2470 to 3341). The number of fills taken into account per beam mode follows: 404 fills for Ramp, 401 for Flat Top, 393 for Squeeze, 356 for Adjust and 274 for Stable Beams.

We define the transmission T as the ratio between $\mathrm{I_{END}}$ and $\mathrm{I_{START}}$, where $\mathrm{I_{START}}$ is the total intensity of one of the two beams at the start of the beam mode and $\mathrm{I_{END}}$ is the total intensity at the end of the beam mode. In particular, $\mathrm{T} = 1$ for zero losses ($\mathrm{I_{END}} = \mathrm{I_{START}}$) and $\mathrm{T} = 0$ if all beam is gone before the end of the mode ($\mathrm{I_{END}} = 0$). In the plots in Fig. 1, the transmission per beam mode is plotted for each fill, in blue for beam 1 (B1) and in red for beam 2 (B2).

The maximum power loss per beam per mode was calculated according to

$$P = \frac{\Delta n}{\Delta t} E_{cal} \qquad \text{with} \qquad E_{cal} = \frac{64\, E_{\mathrm{TeV}}}{4\,\mathrm{TeV}\; 10^{11}\mathrm{p}} \qquad (1)$$

where $\mathrm{E_{cal}}$ is a calibration factor that gives the energy loss per proton at 4 TeV and $\Delta n = n_1 - n_2$ is the intensity decrease in number of protons over the time $\Delta t = t_2 - t_1$ (intensity data from DC beam current transformer, smoothed with a Savitzky-Golay algorithm). The maximum dissipated power is calculated by sliding the time window Δt over the duration of the beam mode under analysis. The calculation is repeated for four different time window lengths: 1 s, 5 s, 20 s and 80 s.

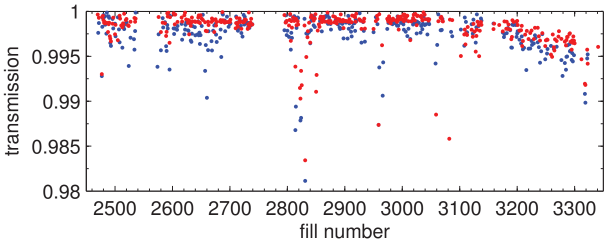
Capture Losses (450 GeV to 500 GeV)

Fig. 1a shows the transmission from 450 to 500 GeV. The transmission is generally worse for B1 than for B2. It can be seen that capture losses improved, especially for B1, when energy matching between the SPS and the LHC was performed at fill 2687. A localized worsening is present after fill 2780, possibly traced back to worse injected beam quality.

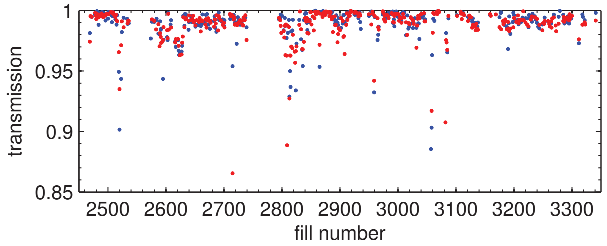
The increase in capture losses towards the end of the run is apparent. A second energy matching was performed to try and improve the situation (fill 3271), but with negligible effect. The increase in losses is probably due to the enhancement of satellite population for ALICE luminosity, performed after fill 3178.

Losses during the Ramp (500 GeV to 4 TeV)

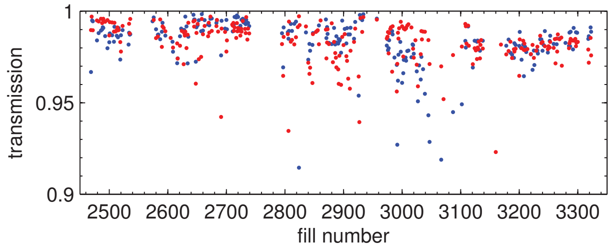
Losses during acceleration (above 500 GeV) are at the percent level as shown in Fig. 1b. Indeed the single beam lifetime decreases appreciably towards the end of the ramp, e.g. when the primary collimators close and the transverse tails are scraped away. This is confirmed by the analysis of



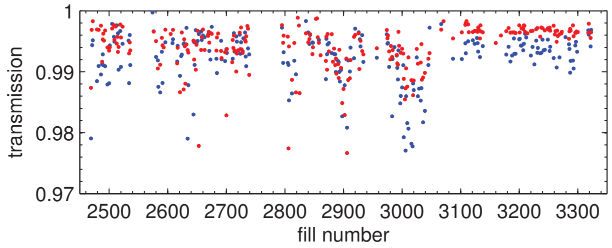
(a) Capture losses.



(b) Ramp losses.



(c) Adjust losses.



(d) Stable beams losses.

Figure 1: Beam losses per mode per 2012 fill (capture, ramp, adjust and stable beams). Note the different vertical scales.

the maximum power loss (see Eqn. 1), highlighting that the peak losses happened at the end of the ramp for almost all fills.

The transmission improved towards the end of the run, when the new Q20 optics was introduced at the SPS for operational LHC beams [3], allowing the transfer of beams with smaller transverse size.

Losses during Flat Top and Squeeze

The time spent at the flat top was rather short for most fills, i.e. few minutes for manual checks on the tune and to load the functions on systems like power converters and collimators. Thus, losses were in general negligible.

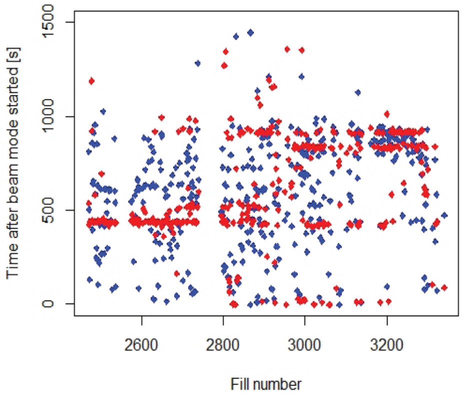


Figure 2: Time at which the maximum power loss (20 s sliding window) happened after the start of the squeeze beam mode. The function length is 925 s.

The B2 lifetime during Flat Top and Squeeze was generally worse than for B1 and slightly worsened around the time at which the octupole polarity was reversed (fill 2924) and the chromaticity increased.

Looking at the maximum power losses with 20 s time window, the peak is very reproducible for B1 ($\approx 10\,\mathrm{kW}$), and less for B2 (generally $< 30\,\mathrm{kW}$). The time in the mode at which the peak power loss happened is very reproducible for B2 (see Fig. 2). In fact, the peak power losses cluster around a few definite times, i.e.: $\approx 420\,\mathrm{s}$ or $\approx \beta^* = 3\,\mathrm{m}$, $\approx 820\,\mathrm{s}$ or $\approx \beta^* = 0.7$–$0.8\,\mathrm{m}$, $\approx 930\,\mathrm{s}$ or $\beta^* = 0.6\,\mathrm{m}$.

Losses during Adjust

In the Adjust beam mode the beams are put into collisions. The main change in 2012 coincided with the use of two collision functions instead of one for stabilization reasons (fill 3114 [4]). Initially the transverse optics gymnastics in Interaction Point (IP) 8 [5] was done at the same time as the separation bumps collapse in all IPs. Later, collisions in IP1, 2 and 5 were established first, followed by the IP8 gymnastics. The change resulted in more reproducible figures for transmission and peak power losses (see Fig. 1c).

Losses at Start of Stable Beams

The transmission in the first 5 minutes in Stable Beams also improved after this change and became much more uniform, as it can be seen in Fig. 1d. In this phase, it is B1 that had usually higher losses than B2. This could be intuitively explained by the fact that the transverse tails of B1 were not scraped as much as the ones of B2 earlier in the cycle or by the fact that B1 suffered from instabilities in most fills (see in later section on bunch-by-bunch differences).

Table 1: Losses per beam mode, comparison between 2011 and 2012. The last line refers to the total transmission, for fills that lasted until stable beams. Statistics for 2011 are calculated over 200 fills, from fill 1615 to fill 2266.

Losses	**2011**		**2012**	
	B1	**B2**	**B1**	**B2**
Capture	0.14%	0.10%	0.52%	0.34%
Ramp	0.71%	0.11%	1.17%	1.22%
Flat top	0.07%	0.02%	0.57%	0.48%
Squeeze	0.08%	0.04%	1.22%	1.99%
Adjust	0.46%	0.30%	1.76%	1.65%
Total	0.81%	0.66%	3.82%	4.74%

Comparison with Losses in 2011

Losses in 2012 were about a factor 10 higher than in 2011 (see Table 1). The 2011 peak power loss analysis indicates that: peak power losses in 2011 are generally a factor 2 to 3 lower than in 2012 (peaks < 30 kW for B1 and < 10 kW for B2); B1 was consistently worse than B2; the clustering at certain times in Squeeze was not observed.

BUNCH-BY-BUNCH DIFFERENCES

The LHC beam is composed of $\approx$ 1380 ($\approx$ 2800) bunches separated by 50 ns (25 ns) beams and bunch-by-bunch differences can be due to different factors, e.g. the production scheme in the injectors, the time spent at the flat bottom during injection, beam-beam effects, etc. In 2011 and 2012 physics fills were with 50 ns bunch separation.

Two main differences in the bunch-by-bunch beam losses were observed: a reproducible loss structure for B1 and additional losses related to transverse emittance increase due to instabilities that developed in many fills in the second part of the run. The B1 loss structure [6] develops during long physics fills and is related to the gaps in the bunch structure, e.g. required for the rise of the fields in the injection and extraction kickers. The beam is injected in several batches from the SPS to the LHC. In particular, the first $\approx$ 30 bunches of each SPS batch in B1 lose up to 10% less in Stable Beams compared to the later bunches (the preceding gap is required by the LHC injection kicker). A clear cause for this bunch-by-bunch difference has not been identified yet. The structure does not correlate easily to long-range beam-beam effects and remains visible after removal of the luminosity burn-off component to the losses.

For many fills at the end of the 2012 proton physics run, it was observed [7] that bunches in B1 could be divided into two families, i.e.: bunches developing a shorter bunch length with higher losses and increased transverse emittance; and bunches getting longitudinally longer with smaller losses and lower values for the transverse emittance. These characteristics built up during collisions and were related to the occurrence of transverse instabilities and emittance blow up for B1 at the end of the squeeze, before bringing the beams into collisions. The effect was not observed on B2.

Other cases of bunch-by-bunch differences were observed throughout 2012 for a few fills, and the causes were found and rapidly corrected, e.g. different settings on the transverse damper during commissioning (e.g. fill 2593) or insufficient beam quality from the injectors (for example, loss of proper longitudinal structure at the PS, fill 3109).

CONCLUSIONS AND FUTURE WORK

Beam losses through the proton physics nominal cycle were non-negligible in 2012. The transmission was on average $\approx 96\%$ to be compared to $\approx 99.3\%$ in 2011. Features in the losses per beam mode per ring could be highlighted: degradation of capture losses towards the end of the run, possibly related to enhanced satellite population; losses of $\approx 1.2\%$ during acceleration, mostly towards the end of the ramp when primary collimator jaws close in; peak power losses at precise moments in the squeeze function for B2; losses in Adjust became much more reproducible since the use of the split collision function.

Bunch-by-bunch differences are present and often reproducible, their causes are not always understood.

A tool for fill-by-fill data analysis e.g. to observe the evolution of the luminosity performance or of the losses on a weekly basis would be extremely useful. This would allow a more prompt reaction to problems that might generate from the drift of parameters and a ready handle to verify the improvement of settings.

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